# AN OPTICAL NETWORK INTEGRATION PLATFORM BASED ON HOLOGRAPHIC SUPER-DENSE WDM FILTERS

**M.S. Shahriar *[1,2], M. Andrews[1] and S. Tseng[1]**
*[1]The Digital Optics Technologies, Inc., Rollimg Meadows, IL 6008*
*[2]EECS Department, Northwestern Univesity, Evanston, IL 60208*
**J. Kuykendall**
*Zenwa, Inc., Sudbury, MA 01776*
**A. Meshal and N. Vallestero**
*United States Army*
*US Army CECOM, AMSRD-CER-ST-DN-SN, Fort Monmouth, New Jersey, 07703*

## ABSTRACT

We have demonstrated the feasibility of realizing an Optical Network Integration Platform (ONIP) that would address the requirements of the Army's FCS and WIN-T programs. The breakthrough networking capabilities represented by this technology is in the ability to filter and multiplex extremely narrow optical channels, on the order of 10 GHz at bandwidths of 5 GHz each and the ability to increase significantly the number of channels that can be carried on a fiber or free space optical transmission facility. The ONIP is a generic, scalable networking device that accepts inputs from wired, wireless or free-space and fiber based communications networks. The design of the ONIP is based on the use of ultra-narrow band, thick holographic filters. Briefly, each filter can combine two optical channels, separated by a frequency as small as 10 GHz. At the input port of the ONIP, two optical frequencies are first combined using a single filter. This is followed by another filter, which combines the first two frequencies with a third frequency. By repeating this process, (N-1) gratings can be used to combine N optical frequencies, representing N input channels. On the output port, this process is reversed. We have successfully demonstrated a six-channel ONIP using thick holographic gratings. The frequencies of the lasers used for this ONIP were each close to 1550 nm, but all distinct from each other. The laser frequencies were controlled using a combination of current and temperature. We have demonstrated channel multiplexed optical communication with this ONIP, using direct modulations as well as wireless devices. The bandwidths of the gratings used for this proof-of-principle system were not very narrow --- each about 50 GHz. However, very recently, we have succeeded in making much narrower gratings (close to 10 GHz). An ONIP based on these narrower devices, operating in the reflection mode, will require the use of an array of super-stable lasers. In collaboration with the telecommunication industry, efforts are currently underway to realize such a laser array, which in turn will be used the demonstrate the finer scale ONIP for potential field deployment.

## 1. INTRODUCTION

The Army's Future Combat Systems program is designated as a networked system of systems. FCS will serve as the core building block within all objective force maneuver units of action to enhance joint and coalition war-fighting capabilities. In order to meet the need for the FCS, we have developed an Optical Network Integration Platform (ONIP). The ONIP is a generic, scalable networking device that accepts inputs from wired, wireless or free-space and fiber based communications networks. The ONIP is capable of being protocol agnostic, interconnecting legacy and future generation networks on a peer-to-peer basis, or through third party industry standard protocol translators, facilitating the interconnection of networks with dissimilar protocols. The ONIP is data-rate insensitive, accommodating terminals or networking devices that operate in ranges from tens of kilobits to tens of gigabits, all within the same box. The ONIP units could be networked through optical and/or wideband RF links and could operate in a fail-safe mode that allows accessing on optical or RF basis as determined by the transmission facilities available. The breakthrough networking capabilities represented by this technology is in the ability to filter and multiplex extremely narrow optical channels, on the order of 10 GHz at bandwidths of 5 GHz each and the ability to increase significantly the number of channels that can be carried on a fiber or free space optical transmission facility. This filtering and

# Report Documentation Page

*Form Approved*
*OMB No. 0704-0188*



| | | |
|---|---|---|
| 1. REPORT DATE<br>**01 NOV 2006** | 2. REPORT TYPE<br>**N/A** | 3. DATES COVERED<br>**-** |

| | |
|---|---|
| 4. TITLE AND SUBTITLE<br>**An Optical Network Integration Platform Based On Holographic Super-Dense Wdm Filters** | 5a. CONTRACT NUMBER<br>5b. GRANT NUMBER<br>5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S) | 5d. PROJECT NUMBER<br>5e. TASK NUMBER<br>5f. WORK UNIT NUMBER |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>**The Digital Optics Technologies, Inc., Rollimg Meadows, IL 6008** | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | 10. SPONSOR/MONITOR'S ACRONYM(S)<br>11. SPONSOR/MONITOR'S REPORT NUMBER(S) |

12. DISTRIBUTION/AVAILABILITY STATEMENT
**Approved for public release, distribution unlimited**

13. SUPPLEMENTARY NOTES
**See also ADM002075., The original document contains color images.**

14. ABSTRACT

15. SUBJECT TERMS

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT<br>**unclassified** | b. ABSTRACT<br>**unclassified** | c. THIS PAGE<br>**unclassified** | **UU** | **7** | |

multiplexing is made possible due to a recent demonstration by us of making efficient gratings in a very thick hologram. We developed the material (PDA: photopolymer with diffusion amplification) that makes it possible to write these gratings, and invented the techniques for writing the gratings necessary for ultra-narrow channel network applications.

The ONIP is expected to find wide use for many applications within DOD, not only for Army networks but also for all branches of services. By using the ONIP as the building block for configuring disparate sub-networks, varying battle-space configurations can be set-up quickly after a combat unit arrives at the remote location and can be scaled up as the needs increase due to an expanded operation.

## 2. DESIGN AND OPERATING PRINCIPLE OF ONIP

A scalable, modular ONIP that can be applied to a large number of applications can best be demonstrated using an example of a conventional circuit switched voice/data service that is to communicate seamlessly with an IP based voice/data network. Even though this is simply an example, this application has wide operational and economic benefits to the Army and other of DOD services, since it will provide a methodology to phase out --- transparently and seamlessly --- legacy circuit switched systems while installing current and future technology IP based voice/data/video systems that are now commercially available.

Figure 1 shows, for example, a facility that has four building complexes, two being served by circuit switched stand alone PABXs and two with IP based exchanges. The four building complexes are served by a fiber ring. At the network control center node of the ring, an enterprise IP-to-circuit-switch / circuit-switch-to-IP translator is located. Though this example shows the nodes as serving building complexes, the same configuration may be used where the nodes are entire Army bases within a region, served by a single (with redundancy) translation facility.

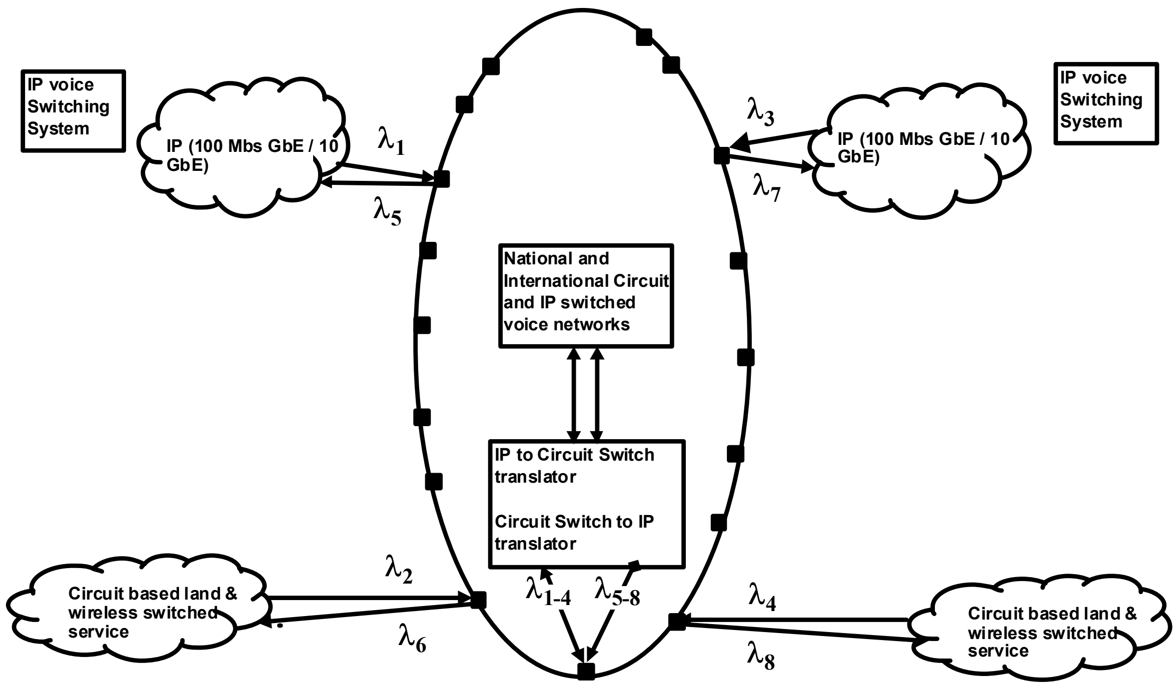


*Figure 1: Networking arrangement using an all optic ring employing passive holographic super dense WDM (SDWDM), showing an example of circuit-switch to IP-voice and IP-voice to circuit-switch translations (user from any site can call any other user from any other site and commercial networks with seamless connections). This is the basic model of the Optical Network Integration Platform (ONIP).*

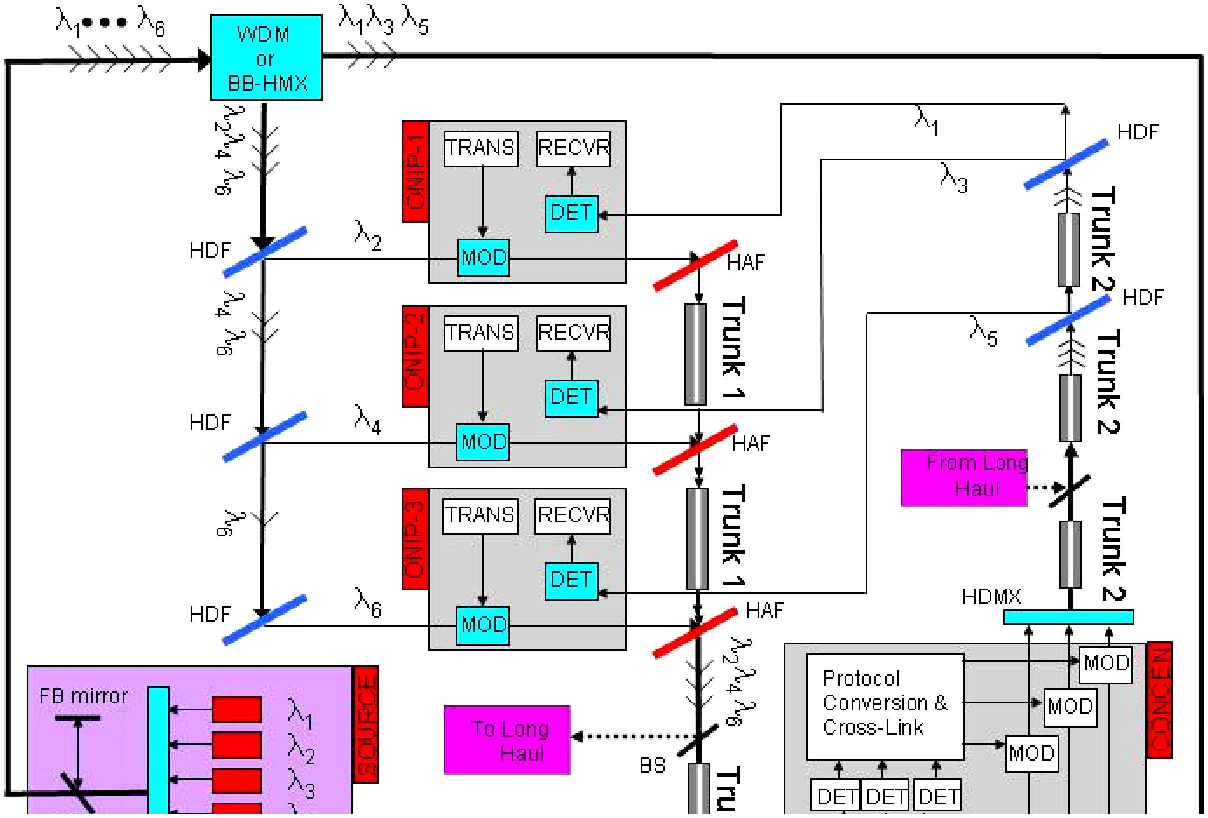

*Figure 2: The explicit detail behind the schematic model of the ONIP (Optical Network Integration Platform) shown in figure 1. Many different types of trunking options (fiber, free-space optics, or wideband wireless) may be used. See text for details.*

The nodes of the ring are served by holography based drop and insert channel units that deliver two or more dedicated wavelengths to and from each remote node and the central network control that are typically 2 to 10 GHz wide. The transmission protocols that are used on each of the dedicated wavelengths would typically be 1 or 10 Gigabit Ethernet for the IP based service and T-3 or OC-12 or OC-48 for the circuit based service. As the optical ring is protocol agnostic, the native protocols of the systems served by the nodes are transported transparently. The enterprise network translation switch will be configured to match the protocols of each of the systems of each of the remote nodes.

The addressing and signaling translation between the IP and circuit switched services takes place through the enterprise translation switch. During a transition phase when circuit based switches are being phased out, the application programming of the enterprise switch would need to be constantly upgraded to reflect the changes made at each remote facility. Though software modifications will be required in the enterprise switch, there would be minimal changes in the holographic based optical ring network that serves as the transport system between the nodes.

Figure 2 shows an explicit view of the ONIP (Optical Network Integration Platform) architecture shown originally in figure 1. As an example, we consider only 3 ONIP's, although in practice many more can be connected in a network. To start with, consider the source, which is created by combining a set (6 for illustration) of laser beams. The number of lasers is given by twice the number of ONIP's to be employed. The lasers may be stabilized via feedback (note that in a particular configuration only a single feedback mirror may be necessary to stabilize all the lasers to the desired Bragg-matched values) to each grating in the HDMX (Holographic Demultiplexer: See figure 4).

The source is split into two groups, one for the input beams, and the other for the output beams. This splitting can be performed either by a conventional broad-band WDM device, or by a broad-band (BB) HMX (Holographic Multiplexer: see figure 4 for details.)

The three beams in the transmission band ( $\lambda_2$, $\lambda_4$, $\lambda_6$) are each dropped sequentially to the corresponding ONIP's, using a holographic add filter (HAF: see figure 3 for details). The trunk needed for this job is not shown explicitly for simplicity. The signal from the ONIP client is then used to modulate the corresponding beam, which in turn is added to the trunk 1 (the trunks can be optical fiber or free-space optical link; they can also be wideband wireless, in which case we have to add an additional element for optical-to-electronic-to-optical cross conversions). Trunk 1 brings all the transmission signals into the control center (CONCEN), which converts each message into an electrical signal. The CONCEN also receives the beams from the receiver band, after splitting them into individual ones. According to the request from the individual ONIP's, CONCEN now cross-connects them, via modulating the appropriate receiver beam. The CONCEN also performs the protocol conversions (e.g., voice-over-IP to circuit-switched-voice, and vice versa) using commercial gateway electronics. The modulated receiver beams are now sent around the network loop via trunk 2, which in turn drops them to the individual ONIP's,

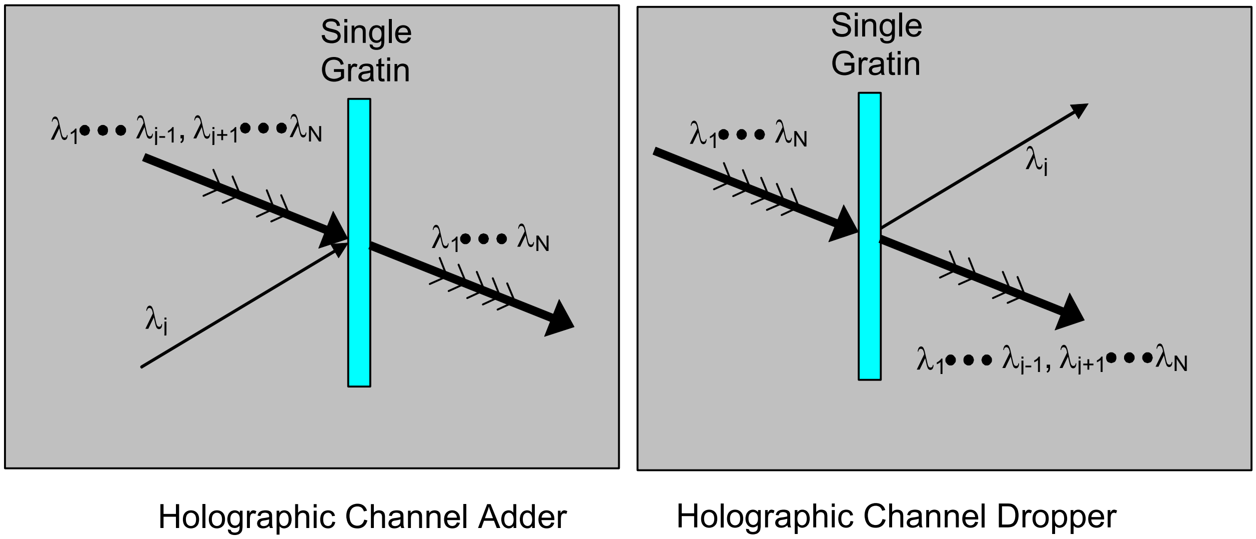


*Figure 3: Schematic illustration of the holographic add-drop filter (HAF and HDF), used extensively in the ONIP architecture detailed in figure 2. See text for details.*

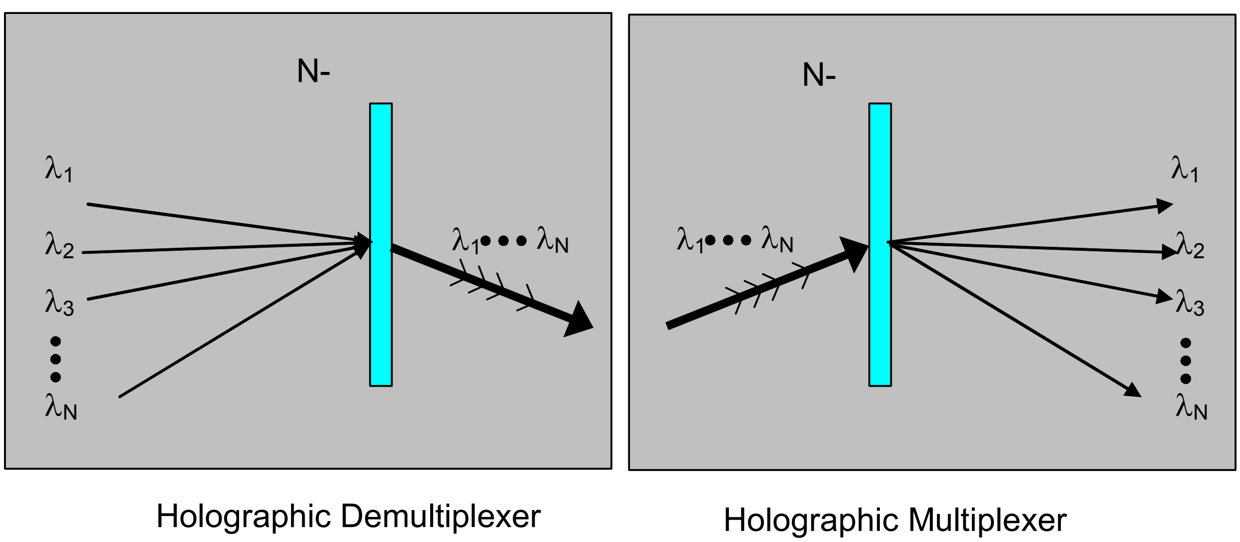


*Figure 4: Schematic illustration of the holographic multiplexer (HMX) and holographic demultiplexer (HDMX), also used extensively in the ONIP architecture detailed in figure 2. See text for details.*

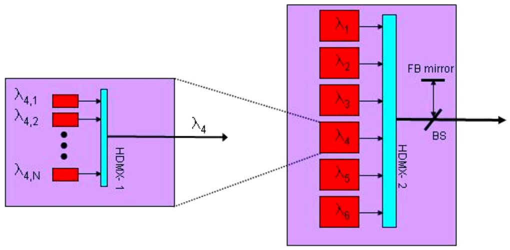


*Figure 5: Exploded view of the source shown in figure 2, allowing for N different clients for each ONIP. Here $\lambda_{4,1}$, for example, represents (a single) wavelength number 1 within the band number 4. See text for details.*

using holographic drop filters (HDF: see figure 3 for details). Each ONIP now detects the corresponding signal, passing them onto its client, in a seamless manner.

In practice, each ONIP can serve multiple clients, as illustrated later on. Before we discuss that, we show the details of the components shown in figure 2. Specifically, figure 3 shows the holographic add-drop filters (HAF and HDF), which are basically the same device, operated in reverse of each other. The filter contains only one grating (as opposed to the HBC, which has multiple gratings). Consider, for example, the HAF, the holographic channel adder. The grating is oriented such that all but one wavelength pass right through it, while the wavelength to be added diffract efficiently into the same direction as the other beams, thus performing the adding. The HDF operates using the reverse of the same principle.

Figure 4 shows the holographic demultiplexer (HDMX) and holographic multiplexer (HMX). The HDMX is the same as what we call the HBC (Holographic Beam Combiner). Briefly, N orthogonal, efficient gratings diffract N non-degenerate frequencies into the same direction. The HMX is simply the HDMX operating in reverse.

As mentioned briefly above, the architecture in figure 2 can accommodate multiple clients. To see how this is possible, consider the source. In the discussion around figure 2, we considered the source to have six distinct frequencies. In practice, each of the wavelength (e.g., $\lambda_4$ ) may actually consist of a *band* of frequencies, as illustrated in figure 5. Such a source can be realized using a two-stage HBC.

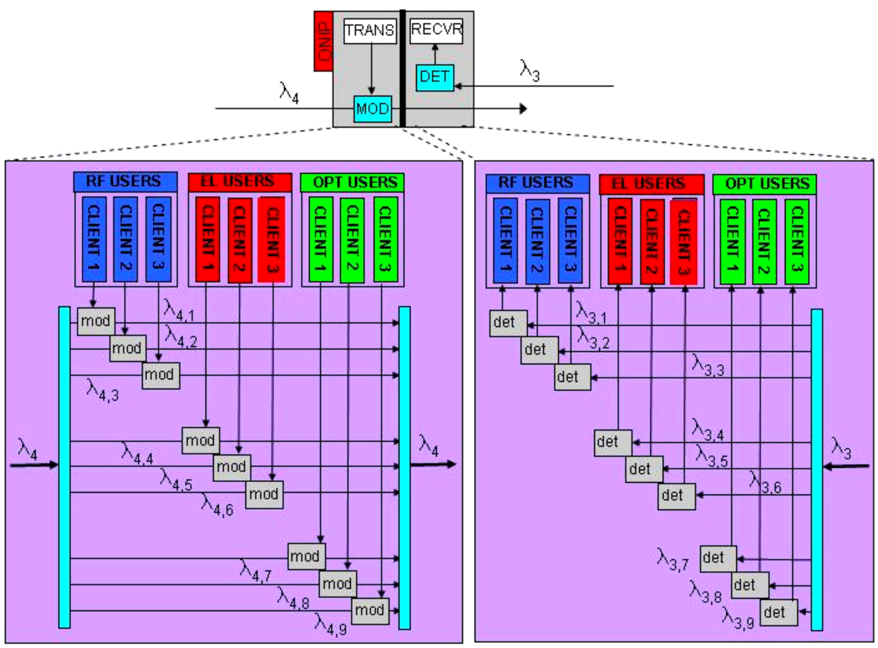


*Figure 6: Exploded view of the ONIP shown in figure 2, allowing for N different clients for each ONIP. Here, we have chosen to use N=9 for illustrative purposes. Here $\lambda_{4,1}$, for example, represents (a single) wavelength number 1 within the band number 4. The N (9) clients are further subdivided into M (3) groups by types. See text for details.*

Figure 6 shows how the details of an individual ONIP look under this condition. Specifically, the ONIP has N (9 for illustration here) clients, which can in turn be grouped in M sets (3 for illustration). The groups can represent different types of clients: e.g. RF based clients, optics based clients, and electrical system based clients, for example. The input frequency band to the ONIP is split into N (9) copies, using an HMX, and modulated separately using information from individual clients. The beams are then recombined using an HMDX before adding its band onto the trunk. The same type of multiplexing is performed on the receiver side, as shown in figure 6. Similar level of multiplexing/demultiplexing is now needed also in the CONCEN in this case.

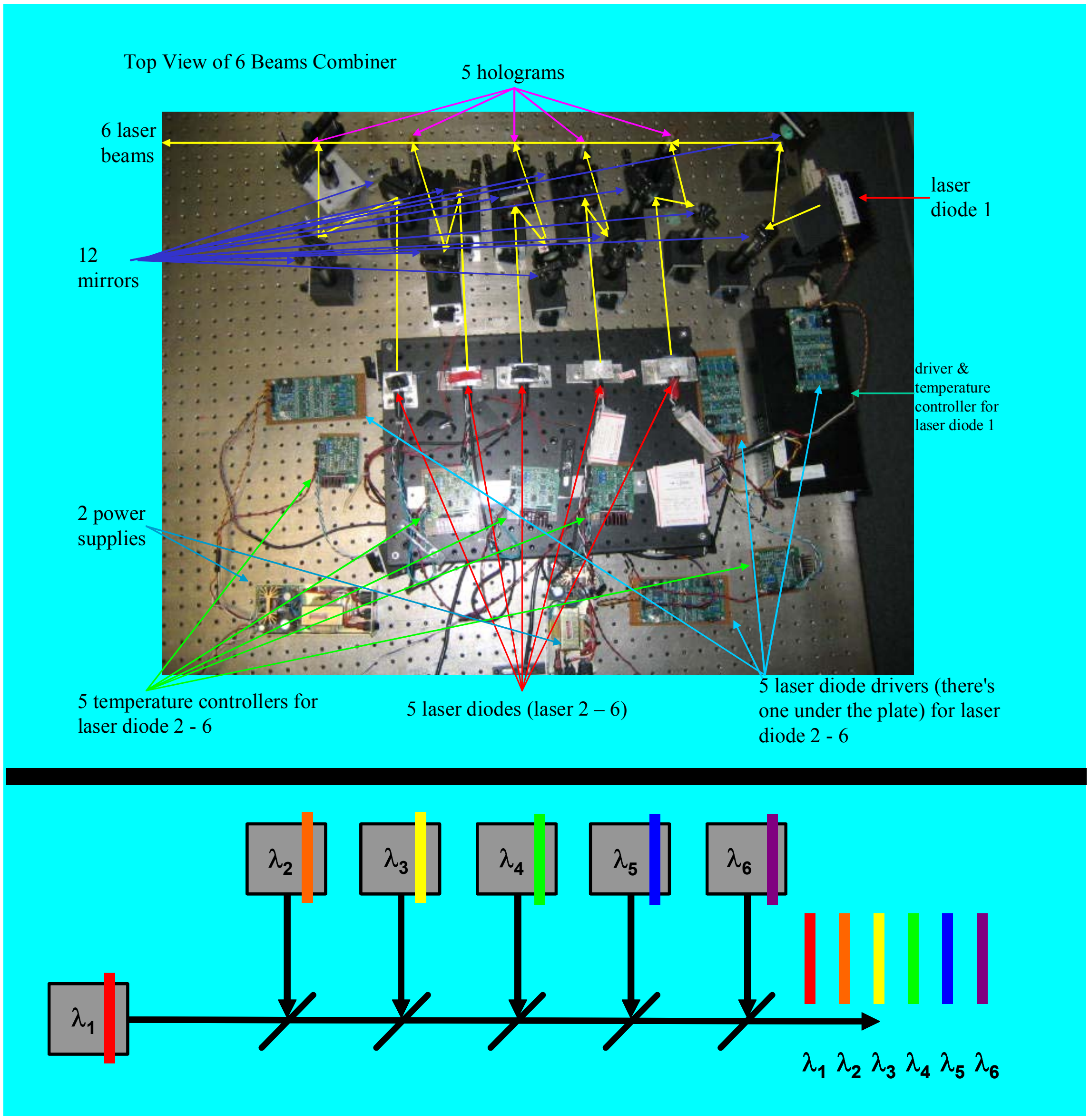


*Figure 7: Schematic illustration (bot) and physical picture (top) of a six channel ONIP.*

## 3. EXPERIMENTAL DEMONSTRATION

As described above, the design of the ONIP is based on the use of ultra-narrow band, thick holographic filters. In one version, many filters can be realized using a single substrate. Alternatively, individual substrates can be used to realize single filters, which in turn can be cascaded to realize the same functionality as that offered by multiple gratings written in a single substrate. Experimentally, the later

approach is much easier to implement, and allows for greater flexibility during operations.

To illustrate explicitly, in this approach, each filter can combine two optical channels, separated by a frequency as small as 10 GHz. Consider first the input port of the ONIP. Here, two optical frequencies are first combined using a single filter. This is followed by another filter, which combines the first two frequencies with a third frequency. By repeating this process, (N-1) gratings can be used to combine N optical frequencies, representing N input channels. On the output port, this process is reversed. A single grating, operating as a drop filter, can be used to access any desired channel, by adjusting the input angle of the beam. For an N channel ONIP, (N-1) gratings are positioned at proper angles to produce an N-port output simultaneously.

Using this approach, we have successfully demonstrated a six-channel ONIP using thick holographic gratings. This is illustrated schematically in the bottom of figure 7. The top of figure 7 shows a picture of the actual device. The frequencies of the lasers used for this ONIP were each close to 1550 nm, but all distinct from each other. The laser frequencies were controlled using a combination of current and temperature. The five gratings employed for combining the lasers at the input port were each made from thick holographic substrates. A sixth grating was used to demonstrate the on-demand channel dropping capacity. Of course, in a field deployable ONIP system, five additional gratings would be employed to provide access to each output channel simultaneously. We have demonstrated channel multiplexed optical communication with this ONIP, using direct modulations as well as wireless devices.

The bandwidths of the gratings used for this proof-of-principle system were not very narrow --- each about 50 GHz. However, very recently, we have succeeded in making much narrower gratings (close to 10 GHz). An ONIP based on these narrower devices, operating in the reflection mode, will require the use of an array of super-stable lasers. In collaboration with the telecommunication industry, efforts are currently underway to realize such a laser array, which in turn will be used the demonstrate the finer scale ONIP for potential field deployment.

**References:**

[1] "Coherent and incoherent beam combination using thick holographic substrates," M.S. Shahriar; J. Riccobono; M. Kleinschmit; J.T. Shen, Opt. Commun., **220**, 1, pp. 75-83(2003).

[2] “Demonstration of a coherent holographic beam combiner”, H.N. Yum, P.R. Hemmer, A. Heifetz, J.T. Shen, J-K. Lee, R. Tripathi, and M.S. Shahriar *Opt. Lett., 30, 3012-3014 (2005)*

[3] “Demonstration of a simple technique for determining the M/# of a holographic substrate by use of a single exposure,” H. N. Yum, P. R. Hemmer, R. Tripathi, J. T. Shen, M. S. Shahriar, Optics Letters, Vol. 29 Issue 15 Page 1784 (August 2004)